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A large CO and HCN line survey of Luminous Infrared Galaxies

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Abstract A large CO, HCN multi-transition survey of 30 Luminous Infrared Galaxies ($L_{IR} > 10^{11}\,L_\odot$) is nearing completion with the James Clerk Maxwell Telescope (JCMT) on Mauna Kea (Hawaii), and the IRAM 30-meter telescope at Pico Veleta (Spain). The CO J=1–0, 2–1, 3–2, 4–3,6–5, ^{13}CO J=2–1, HCN J=1–0, 3–2, 4–3 observations, resulting from $\sim$ 250 hours of JCMT, $\sim$ 100 hours of 30-m observing time and data from the literature constitute *the largest extragalactic molecular line survey to date*, and can be used to address a wide range of issues and eventually allow the construction of reliable Spectral Line Energy Distributions (SLEDs) for the molecular gas in local starbursts. First results suggest that: a) HCN and HCO$^+$ J=1–0 line luminosities can be poor mass estimators of dense molecular gas ($n \geq 10^4\,cm^{-3}$) unless their excitation is accounted for, b) CO cooling of such gas in ULIRGs may be comparable to that of the CII line at 158$\,\mu$m, and c) low excitation of the *global* molecular gas reservoir remains possible in such systems. In such cases the expected low CO $J+1 \rightarrow J$ line luminosities for $J+1 \geq 4$ can lead to a strong bias against their detection from ULIRGs at high redshifts.

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1 Introduction

The importance of Luminous Infrared Galaxies (hereafter LIRGs) as the sites of the most extreme local star formation events ([9]) makes them the best available templates for similar events in the distant Universe. Moreover their compact CO-emitting regions ([1]) makes them ideal for multi-line studies of their global molecular gas reservoir up to very high frequencies (where the high-excitation molecular lines lie) since the resulting narrow beams of today's single dish radio telescopes can still measure their total line fluxes with single pointings. Our sensitive CO J=2–1, 3–2, 4–3, 6–5, ^{13}CO J=2–1 and HCN J=3–2 and 4–3 line observations with the JCMT and the IRAM 30-m telescope for $\sim$ 30 LIRGs, combined with available CO and HCN J=1–0 data from the literature, will allow for excellent new constraints on the state of their global molecular gas reservoirs. More specifically the high-J CO and the three HCN transitions can probe the excitation and mass of the dense ($n \geq 10^4\,cm^{-3}$) gas, considered as the immediate fuel of their prodigious star formation ([10], [3]). The completion of our CO J=4–3 and J=6–5 observations and follow-up observations of still higher rotational CO, ^{13}CO and HCN transitions with *Herschel* will ultimately allow the deduction of robust SLEDs for the star-forming molecular gas of LIRGs in the local Universe. These can then be used to uncover any universal aspects of the star-formation/molecular gas interplay in galaxies and find the best rest-frame mm/sub-mm lines for detecting and imaging the numerous LIRGs that will be found at high redshifts in future deep mm/sub-mm continuum surveys ([5]).

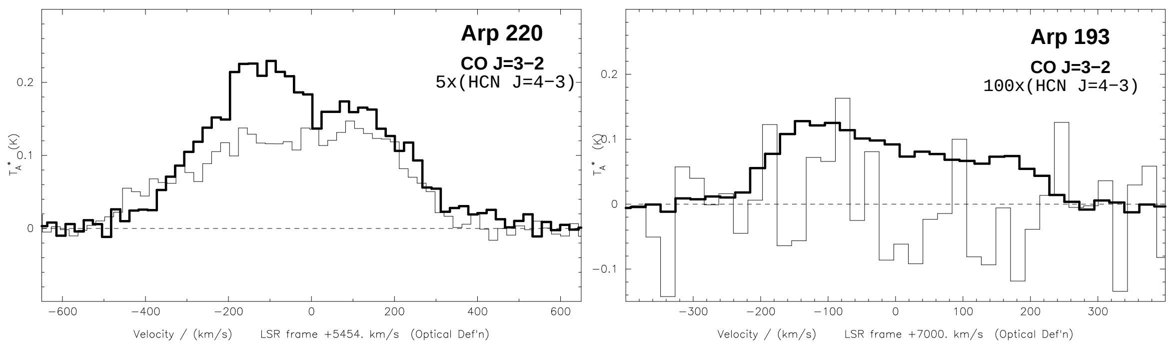

Fig. 1 HCN J=4–3 (scaled by the numbers in the upper right of each panel) and CO J=3–2 spectra of four LIRGs. The HCN (4–3)/(1–0) brightness temperature ratio $r_{43}(\mathrm{HCN})$ is found to vary from $r_{43}(\mathrm{HCN}) \leq 0.1$ (Arp 193) to $r_{43}(\mathrm{HCN}) \sim 0.8$ (Arp 220).

Table 1 HCN vs HCO$^+$ line ratios in Arp 220 and NGC 6240

Galaxy	HCN$\frac{(4-3)}{(1-0)}$	HCN$\frac{(3-2)}{(1-0)}$	HCO$^+\frac{(4-3)}{(1-0)}$	HCO$^+\frac{(3-2)}{(1-0)}$
Arp 220	0.8 ± 0.2	1.0 ± 0.3	0.33 ± 0.10	0.27 ± 0.10
NGC 6240	0.6 ± 0.2	1.0 ± 0.3	0.21 ± 0.06	0.24 ± 0.08

2 HCN versus HCO$^+$ lines as dense gas mass tracers

The rotational transitions of the HCN and HCO$^+$ molecules with their high dipole moments are currently the best (i.e. most luminous) dense gas tracers in LIRGs. An HCN J=1–0 line survey of such galaxies ([3]) has even revealed a potentially constant star formation efficiency ($\propto L_{IR}/M_{dense}(H_2)$) for molecular gas at densities $n \geq 10^4\,\mathrm{cm^{-3}}$, attributed to such a gas phase being the direct fuel of star formation in molecular clouds ([13]). Recent studies have inserted some doubt as to whether HCN lines are good tracers of such a gas phase and suggested those of HCO$^+$ instead ([2]). Our survey reveals a large range of HCN line excitation in LIRGs with otherwise similar IR, CO and HCN J=1–0 luminosities (Figure 1). In the case of Arp 193 the observed very low HCN (4–3)/(1–0) line ratio (its HCN 4–3 is >100 times weaker than its CO J=3–2 line!) *is compatible with the complete absence of a massive and dense molecular gas phase.* On the other hand for the two archetypal ULIRGs Arp 220 and NGC 6240 the HCN ratios are significantly larger than the corresponding ones (in rotational level) of HCO$^+$ (Table 1). This, along with the fact that HCO$^+$ rotational transitions also have $\sim 5-7$ times lower critical densities than those of HCN, signifies that the latter is tracing a denser gas phase and may thus may remain as the most suitable gas mass tracer in galaxies once the excitation of its rotational lines is properly accounted for.

3 The dense molecular gas in Mrk 231

The prototypical ULIRG/QSO Mrk 231 is the first object in our sample for which the full set of line observations

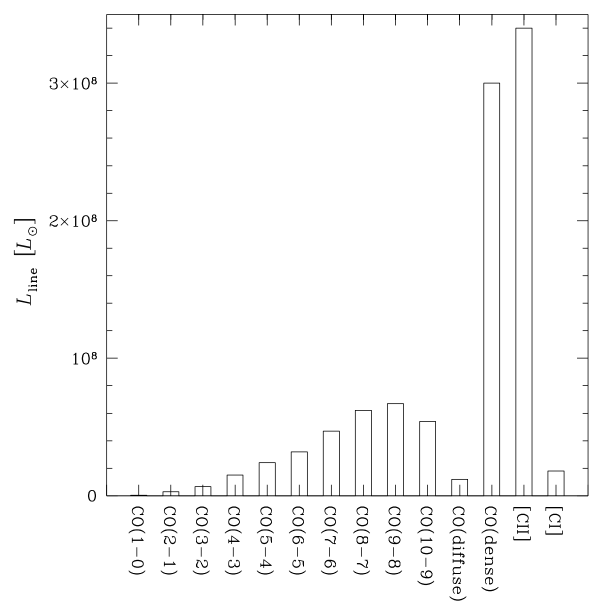

Fig. 2 CO, CI, CII cooling contributions in the ULIRG/QSO Mrk 231

has been completed, allowing for a unique view into the global excitation conditions of its molecular gas. Analysis of the relative strengths of the CO J=1–0, 2–1, 3–2, 4–3, 6–5 and HCN J=1–0, 4–3 lines (and ^{13}CO J=2–1 from the literature,[4]) finds the low-J CO lines dominated by diffuse ($n \sim$ few $\times 10^2\,\mathrm{cm^{-3}}$), and warm ($T_k \sim 90-100\,\mathrm{K}$) gas, while the high-excitation CO J=6–5, 4–3 and the HCN transitions trace a denser ($\sim (1-3)\times 10^4\,\mathrm{cm^{-3}}$) phase with somewhat lower temperatures ($T_k \sim 50-70\,\mathrm{K}$). The latter dominates the total molecular gas mass in Mrk 231, and its total CO line cooling is similar to that of the CII line at 158 μm (Figure 2). *This suggests a different thermal balance to that of lower IR-luminosity galaxies,* and may explain the relative weakness of the CII cooling line in such systems as a result of the dominance of dense Photon Dominated Regions (PDRs) for most of their molecular gas ([6]).

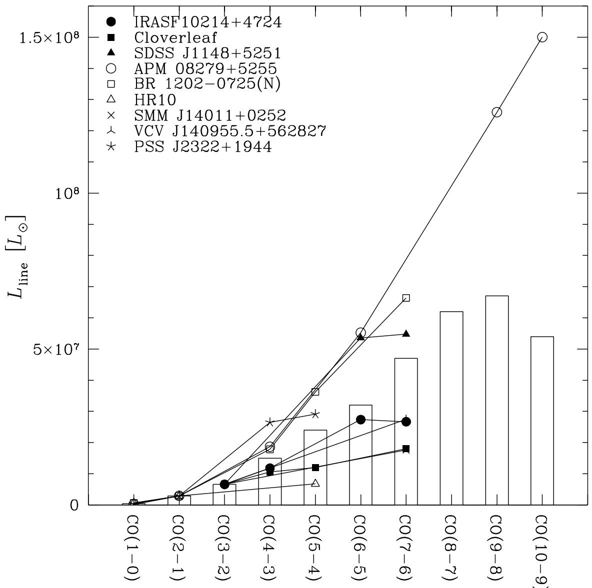

Fig. 3 CO line luminosities of various high-redshift objects compared to the Mrk 231 CO dense gas SLED template (bars). Luminosities are normalized to those of Mrk 231 at either CO J=3–2 or J=2–1. Line fluxes for the various objects are taken from the literature ([11], [8]).

3.1 A comparison with high-z starbursts

The high-J CO and the HCN lines detected in Mrk 231 provide good constraints on radiative transfer models which then allow a good CO SLED to be constructed. Its comparison with objects at high redshifts shows that despite the high excitation of its dense molecular gas its CO SLED stands as rather average (Figure 3). However, strong lensing (affecting several objects in Figure 3) can selectively amplify the highly excited CO line emission of compact starburst regions at the expence of a much more extended low-excitation non-star forming molecular gas phase (e.g. [12]). Furthermore, the high-J CO observations usually conducted after spectroscopic redshifts of high-z objects become available may select mostly from a subset of starbursts where the (star-forming)/(non star-forming) H_2 gas mass ratio (expected to vary strongly in the several merger systems among LIRGs) is particularly large. The limited sensitivity of today's cm and mm/sub-mm single dish telescopes and interferometers will further accentuate the aforementioned biases, which may thus *produce CO SLEDs at high redshifts which are biased towards the high excitation regime*, and are thus unrepresentative of the full excitation range in star-forming galaxies.

In that respect CO (and HCN) SLEDs of local ULIRGs, established from observationally well-sampled J-ladders of rotational transitions, are indispensible as benchmarks unaffected by the aforementioned biases.

Table 2 CO line ratios of a "warm" and a "cold" ULIRG

Galaxy	$\mathrm{CO}\frac{(2-1)}{(1-0)}$	$\mathrm{CO}\frac{(3-2)}{(1-0)}$	$\mathrm{CO}\frac{(4-3)}{(1-0)}$	$\frac{^{12}\mathrm{CO}}{^{13}\mathrm{CO}}$
17208-0014	1.02 ± 0.22	0.72 ± 0.17	0.74 ± 0.23	≥ 35
05189-2524	0.32 ± 0.08	0.24 ± 0.07	< 0.32	6 ± 2

4 A "cold" and a "warm" ULIRG

Molecular gas excitation at levels far below those found in Mrk 231 or other such galaxies used as templates for high redshift starbursts (e.g. Arp 220), have been uncovered by our ongoing survey, further underlying the need for local CO SLEDs to be established for a large sample of local LIRGs.

The two ULIRGs ($L_{\rm IR} > 10^{12}\,L_\odot$) IRAS 17208-0014 and IRAS 05189-2524 have been found to have very different CO line excitation (Figure 4) despite similar IR continuum and CO J=1–0 line luminosities and similar $S_{60\,\mu\rm m}/S_{100\,\mu\rm m}$ ratios. For IRAS 17208-0014 the CO brightness temperature ratios measured are typical for the high-excitation star forming molecular gas found in many such galaxies, but those found for the "cold" IRAS 05189-2524 are surprisingly typical of the quiescent molecular clouds found in the Milky Way disk (Table 2). One-phase radiative transfer models using the Large Velocity Gradient (LVG) approximation and constrained by the line ratios of IRAS 17208-0014 are compatible with densities of $\mathrm{n} \sim 10^3\,\mathrm{cm}^{-3}$ and mostly warm $T_k \sim (70-100)\,\mathrm{K}$. The high ^{12}CO/^{13}CO J=2–1 ratio measured for this merger system (Table 2) is responsible for the low CO J=1–0 optical depths ($\tau_{10} \leq 0.5$) of this gas phase, a result of its high temperatures and large average velocity gradients $\mathrm{dV/dR} \sim 30\,\mathrm{km\,s^{-1}\,pc^{-1}}$ (for an abundance of $[\mathrm{CO/H_2}] = 10^{-4}$). The latter corresponds to a parameter $K_{\rm vir} = \frac{(\mathrm{dV/dR})_{\rm obs}}{(\mathrm{dV/dR})_{\rm virial}} \sim 30-50$, typical of an unbound gas phase ([7]). It is also worth noting that the high (4–3)/(1–0) CO ratio (comparable to that of CO(3–2)/(1–0)) cannot be accounted by a single gas phase model and probably signifies the emergence of a second warmer and denser phase. In several LIRGs (e.g. Mrk 231) such a phase has been found to dominate CO $\mathrm{J}+1 \rightarrow \mathrm{J}$, $\mathrm{J}+1 \geq 4$ and HCN line emission and containing most of their molecular gas mass, and is most likely the direct fuel of their prodigious star formation.

The CO emission in IRAS 05189-2524 on the other hand is compatible with gas of $\mathrm{n} \sim 100\,\mathrm{cm}^{-3}$, $T_k \sim 15\,\mathrm{K}$, and $K_{\rm vir} \sim 1$, typical of the quiescent and mostly self-gravitating molecular clouds found in the Galactic disk immersed in a FUV radiation field of $G_\circ \sim 1$ (Habing units). In such conditions high-J CO lines are expected to be very faint with $\mathrm{CO(J+1-J)/(1-0)} \leq 0.01$ for $\mathrm{J}+1 \geq 4$ for the bulk of the molecular gas. This is much lower than that expected from CO SLEDs of other ULIRGs such as Mrk 231 or Arp 220 or indeed most high redshift objects ([8]), with only the extremely red object HR 10 coming close (Figure 3).

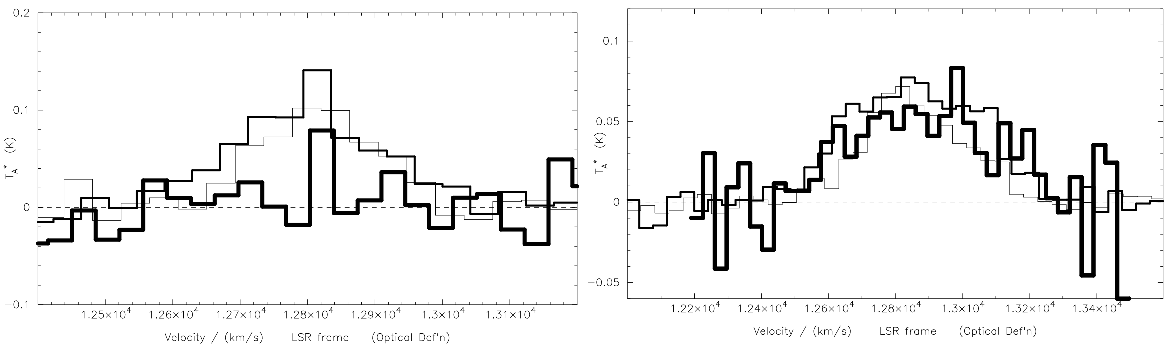

Fig. 4 CO J=4–3, 3–2 and 2–1 spectral lines (plotted with declining line thickness) for the "cold" IRAS 05189-2524 (left panel) and the "warm" IRAS 17208-0014 (right panel) galaxies.

Thus starburst galaxies at high resdshifts with similar CO SLEDs to that of IRAS 05189-2524 *would remain undetected by typical high-J CO observations with today's radio telescopes*, even after scaling their CO line fluxes by their ~ 10 times higher IR luminosities. One of the goals of the CO and HCN multi-transition survey of LIRGs is to find how often such low-excitation molecular SLEDs occur in starbursts, and seek out correlations with other galaxy characteristics (e.g. merger status, starburst age, dust temperatures). This may in turn shed some light into how otherwise vigorously star-forming galaxies can harbor large amounts of low-excitation molecular gas.

5 Conclusions

We report preliminary results from our ongoing CO and HCN multi-transition of 30 local LIRGs, the largest such survey to date. These can be summarized as follows,

– A large range of HCN line excitation precludes the simple use of the HCN or HCO^+ J=1–0 line luminosity as a dense gas mass tracer.
– In the two cases of Arp 220 and NGC 6240, the HCN versus the HCO^+ line excitation suggests the former tracing the densest gas phase.
– In the ULIRG/QSO Mrk 231 the luminous CO J=4–3 and J=6–5 line emission emanates from a different gas phase than the one dominating the low-J CO transitions. In that phase total CO line cooling is comparable to that of the CII line at $158\,\mu$m. If confirmed for more such galaxies this raises the possibility of a very different thermal balance than that seen in lower IR-luminosity systems where the CII line is the dominant coolant.
– The discovery of very low CO excitation in the ULIRG IRAS 05189-2524 raises the possibility of a large excitation bias against detecting similar objects at high redshifts via their high-J CO line emission.

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